Primordial Nucleosynthesis Constraints on Z' Properties

Hye-Sung Lee

(University of Wisconsin - Madison)

based on work with V. Barger and P. Langacker
[Phy. Rev. D 67, 075009]

- Our Z' model
- Decoupling of a Particle
- Big Bang Nucleosynthesis
- Numerical Results
- Conclusion

E_6-motivated Z' Model

Many models from String theory or GUT predict additional neutral gauge bosons (Z').

TeV-scale Z' models can solve μ problem in MSSM. ($\mu \hat{H}_1 \cdot \hat{H}_2 \to h_s \hat{S} \hat{H}_1 \cdot \hat{H}_2$)

Especially, some String compactifications lead to E_6 gauge group.

$$\begin{aligned} E_6 &\to SO(10) \times U(1)_\psi \\ &\to SU(5) \times U(1)_\chi \times U(1)_\psi \\ &\to \{\text{SM group}\} \times U(1)_\chi \times U(1)_\psi \end{aligned}$$

But, canonical E_6 GUT is hard to lead to TeV-scale Z' since E_6 exotics at TeV-scale lead to too rapid proton decay.

In any case, taking E_6 charge assignments is a safe way to introduce an anomaly-free $U(1)'$ model.

Our Model

We assume only one linear combination, $U(1)'$ survives at TeV-scale.

- gauge boson of $U(1)'$: Z'
- charge of $U(1)'$: $Q = Q_\chi \cos\theta_{E_6} + Q_\psi \sin\theta_{E_6}$ $\left(\theta_{E_6}\text{ : mixing angle of } U(1)_\chi \text{ and } U(1)_\psi\right)$
- We take coupling constant and charges from (anomaly-free) E_6 GUT.

$$g'_Z = \sqrt{\frac{5}{3}} g_Z \sin\theta_W$$

$$\left(\text{where } g_Z \equiv \sqrt{g_1^2 + g_2^2}\right)$$

- Family-universal $U(1)'$ charges :

Field	Q_χ	Q_ψ
$\binom{u_L}{d_L}$	$-\frac{1}{2\sqrt{10}}$	$\frac{1}{2\sqrt{6}}$
u_R	$\frac{1}{2\sqrt{10}}$	$-\frac{1}{2\sqrt{6}}$
d_R	$-\frac{3}{2\sqrt{10}}$	$-\frac{1}{2\sqrt{6}}$
$\binom{\nu_L}{e_L}$	$\frac{3}{2\sqrt{10}}$	$\frac{1}{2\sqrt{6}}$
ν_R	$\frac{5}{2\sqrt{10}}$	$-\frac{1}{2\sqrt{6}}$
e_R	$\frac{1}{2\sqrt{10}}$	$-\frac{1}{2\sqrt{6}}$

- Non-zero ν_R charges: Ordinary seesaw forbidden (since $m_{\nu_R} \lesssim U(1)'$ breaking scale) except for a θ_{E_6} that makes $Q(\nu_R) = 0$.

- ν_R in our model:
  - 3 Dirac particles
    $(m_\nu \bar{\nu}_L \nu_R + h.c.)$
  - negligibly small mass
    (by some mechanism such as higher-dim operator or large extra dim.)
  - SM singlet
    (couples only to Z')

Z-Z' Mixing

After EW and $U(1)'$ symmetry breaking, 2 neutral massive gauge bosons Z and Z' can mix (with mixing angle δ).

$$\begin{pmatrix} Z_1 \\ Z_2 \end{pmatrix} = \begin{pmatrix} \cos\delta & -\sin\delta \\ \sin\delta & \cos\delta \end{pmatrix} \begin{pmatrix} Z \\ Z' \end{pmatrix}$$

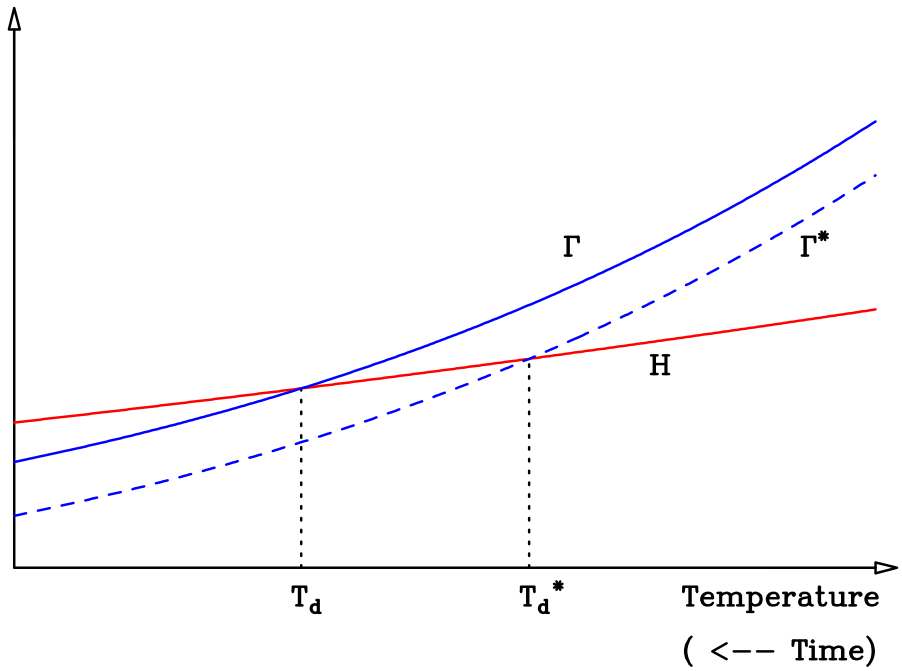
Accelerator Limit

- Current collider limit:
  - $|\delta| < (2-3) \times 10^{-3}$
  - $M_{Z_2} > (500-800)\ GeV$

- Tevatron RunII:
  - can observe $Z' < 1\ TeV$

- Future Collider:
  - can observe $Z' < 5\ TeV$

Decoupling of a Particle



$$\begin{cases} \Gamma(T) & : \text{ interaction rate of particle A} \\ H(T) & : \text{ cosmological expansion rate} \end{cases}$$

- For $\Gamma > H$, ptl A is in equilibrium.
- For $\Gamma < H$, ptl A is decoupled.
- Decoupling Temperature of ptl A : T_d

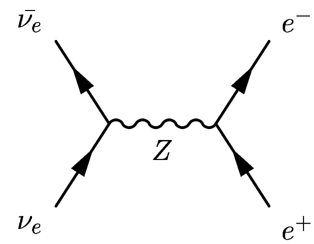
$$\Gamma(T_d) = H(T_d)$$

(T_d carries information about interaction of ptl A)

Interaction Rate $\Gamma(T)$

- For SM neutrino:

  $\Gamma(T) \equiv n \langle \sigma v \rangle \approx G_W^2 \; T^5$



  $G_W \propto \frac{g_Z^2}{M_Z^2}$: weak coupling constant

- For ν_R (which couples only to Z'):

  $G_{SW} \propto \frac{g_Z'^2}{M_{Z'}^2}$: super-weak coupling constant

  $G_{SW} \ll \; G_W$ (because $M_{Z'} \gg M_Z$)

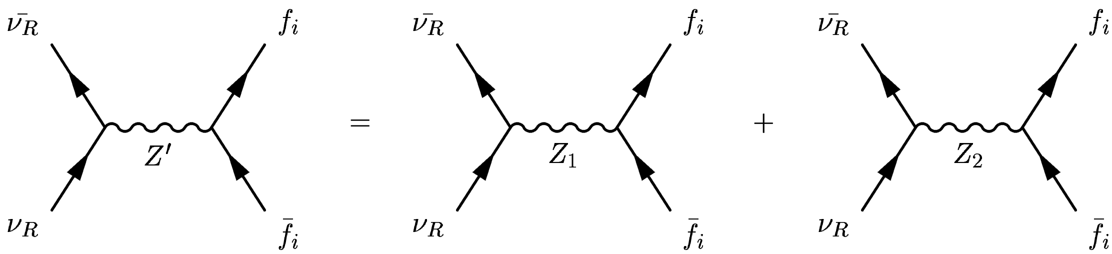
  $\longrightarrow$ smaller $\Gamma(T)$
  $\longrightarrow$ earlier decoupling (higher T_d)

- $M_{Z'} \Longleftrightarrow T_d(\nu_R)$ (from above)

- $T_d(\nu_R) \Longleftrightarrow \Delta Y$ (BBN will provide)

(Steigman, Olive and Schramm, 1979)

Interaction Rate for ν_R



$$\sigma(\bar{\nu}_R \nu_R \to \bar{f}_i f_i)$$
$$= N_C^i \frac{s\beta_i}{16\pi} \left\{ \left(1 + \frac{\beta_i^2}{3}\right) \left((G_{RL}^i)^2 + (G_{RR}^i)^2\right) + 2\left(1 - \beta_i^2\right) G_{RL}^i G_{RR}^i \right.$$

$$\left(\begin{array}{l} G_{RL}^i = g_Z'^2 Q(\nu_R) Q(f_{iL}) \left(\frac{\sin^2\delta}{M_{Z_1}^2} + \frac{\cos^2\delta}{M_{Z_2}^2}\right) \\ \qquad - g_Z' g_Z Q(\nu_R) Q_Z(f_{iL}) \left(\frac{\sin\delta\cos\delta}{M_{Z_1}^2} - \frac{\sin\delta\cos\delta}{M_{Z_2}^2}\right) \\ \\ N_C^i : \text{color factor of particle } f_i. \\ \beta_i \equiv \sqrt{1 - 4m_{f_i}^2/s} \;\; : \text{relativistic velocity of } f_i \end{array} \right)$$

- In the no-mixing ($\delta = 0$) and massless particles ($\beta_i = 1$) limit,

$$\sigma \;\to\; N_C^i \frac{s}{12\pi} \underbrace{\left(\frac{g_Z'^2}{M_{Z'}^2}\right)^2 Q(\nu_R)^2 \left(Q(f_{iL})^2 + Q(f_{iR})^2\right)}_{G_{SW}^2 \;\propto\; \left(\frac{g_Z'^2}{M_{Z'}^2}\right)^2}$$

- Interaction rate: (channels up to b-quak)

$$\Gamma(T) = \sum_i \Gamma_i(T) = \sum_i n_{\nu_R} \left\langle \sigma v(\bar{\nu}_R \nu_R \to \bar{f}_i f_i) \right\rangle$$

(with $u-$, $d-$ channels replaced with π under quark-hadron transition temperature)

Cosmological Expansion Rate $H(T)$

$$H(T) \propto \sqrt{G_N \rho(T)}$$

During Radiation Dominated epochs,

$$\rho(T) = \frac{1}{2}\rho_\gamma(T) g(T)$$

with

$$\begin{aligned} \rho_\gamma &= aT^4 : \text{ photon energy density} \\ g(T) &= \sum_B g_B \left(\frac{T_B}{T}\right)^4 + \sum_F \frac{7}{8} g_F \left(\frac{T_F}{T}\right)^4 \\ &: \text{ effective degree of freedom} \end{aligned}$$

- $g_{B,F}$: DOF of each Boson, Fermion ($g_\gamma = 2,\ g_e = 2 \times 2,\ g_q = 2 \times 2 \times 3$)
- $T_{B,F}$: Temperature of each Boson, Fermion (In equilibrium, $T_{B,F} = T$ After decoupling, $T_{B,F} \propto V^{-1/3}$)

$g(T)$ at BBN ($T \approx 1$ MeV)

- SM prediction :

$$
\begin{aligned}
g_{SM}(T) &= g_{\gamma}\left(\frac{T}{T}\right)^4 + \frac{7}{8}(g_e + 3g_{\nu})\left(\frac{T}{T}\right)^4 \\
&= \frac{43}{4}
\end{aligned}
$$

- Difference from observation :

$$
\begin{aligned}
\Delta g &\equiv g_{\text{exp}}(T) - \frac{43}{4} \\
(&= 0 + \frac{7}{8}\Delta N_{\nu}\ g_{\nu}\left(\frac{T}{T}\right)^4)
\end{aligned}
$$

- In number of additional weak int. ν's:

$\Delta N_{\nu} \lesssim (0.3 - 1)$: typical range

from observed ${}^4He$ abundance discrepancy

$(\Delta Y \sim 0.013 \Delta N_{\nu})$

(most stringent limit on weak int. neutrino before 1990 LEP Z-width measurement)

For Super-weakly interacting particles

- Assume observed ΔY (^4He abundance discrepancy) comes from diluted contribution of (super-weakly interacting) ν_R's.

$$\begin{aligned} \Delta g &= \sum_{\Delta F} \frac{7}{8} g_F \left(\frac{T_F}{T}\right)^4 = 3 \times \frac{7}{8} g_{\nu_R} \left(\frac{T_{\nu_R}}{T}\right)^4 \\ &= \Delta N_\nu \times \frac{7}{8} g_{\nu_R} \left(\frac{T}{T}\right)^4 \end{aligned}$$

$$\Delta N_\nu = 3 \left(\frac{T_{\nu_R}}{T_{BBN}}\right)^4 = 3 \left(\frac{g(T_{BBN})}{g(T_d(\nu_R))}\right)^{4/3}$$

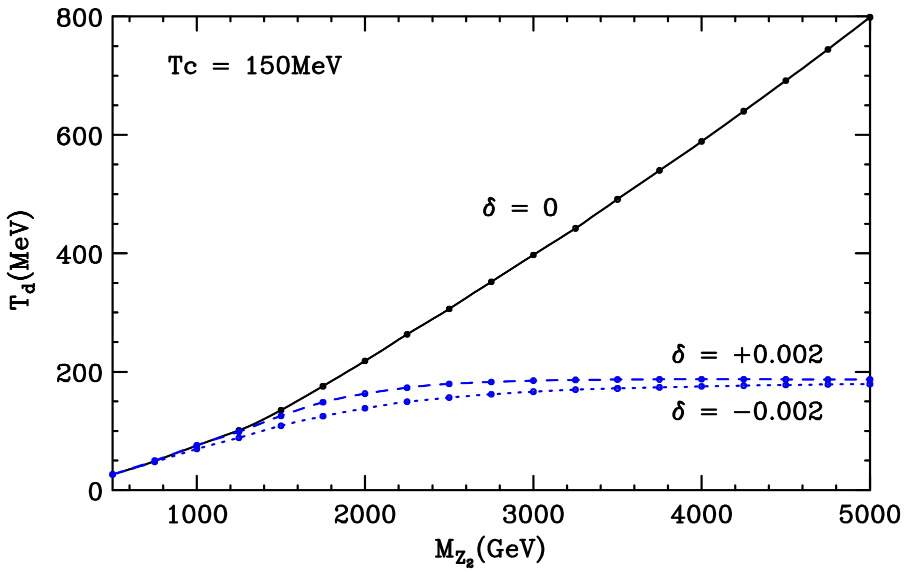
(from entropy conservation)

- Information about $T_d(\nu_R)$ from BBN's ΔN_ν (or $\Delta Y \sim 0.013 \Delta N_\nu$)

- $M_{Z_2} \Longleftrightarrow T_d(\nu_R) \Longleftrightarrow \Delta N_\nu$

Numerical Result

For η model ($\theta_{E_6} \simeq 1.71\pi$) :

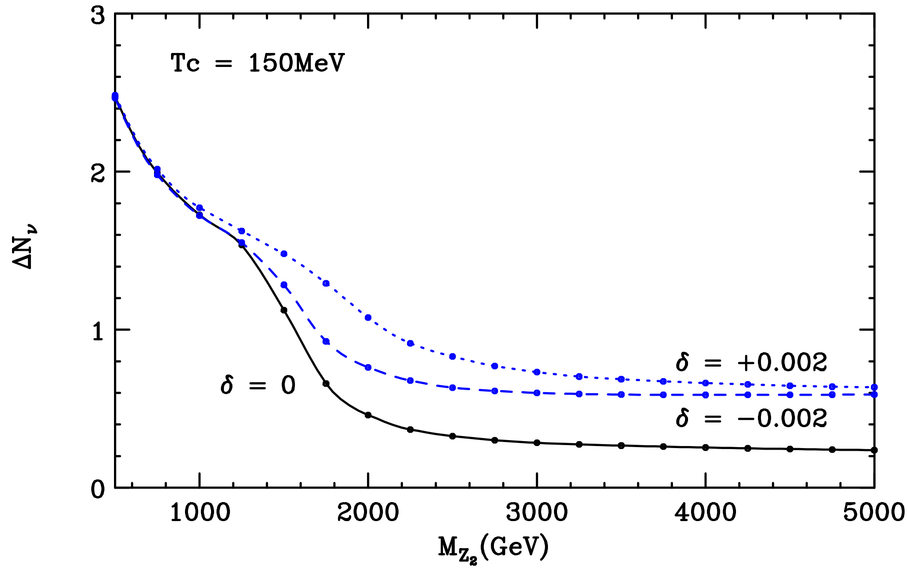


from $H(T) = \Gamma(T) \longrightarrow T_d(\nu_R)$

- No Z-Z' mixing ($\delta = 0$) : keeps increasing (heavier $Z' \rightarrow$ weaker $\Gamma \rightarrow$ higher T_d)

- Maximal mixing ($|\delta| = 0.002$) : becomes flat

$$\left(\sqrt{\sigma} \propto \frac{\sin^2\delta}{M_{Z_1}^2} + \frac{\cos^2\delta}{M_{Z_2}^2} \rightarrow \frac{\sin^2\delta}{M_{Z_1}^2} \text{ (const.)} \right)$$



from previous plot with relation

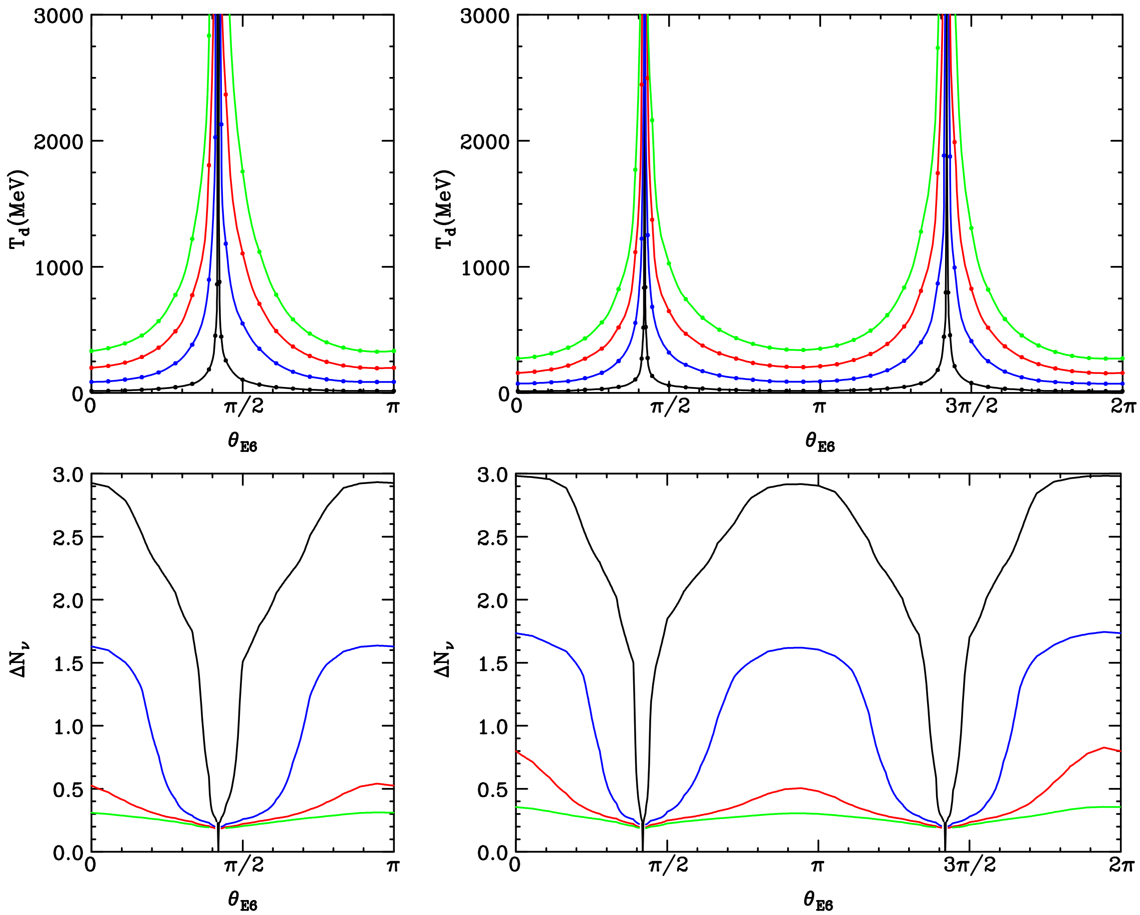
$$\Delta N_\nu = 3 \left(\frac{g(T_{BBN})}{g(T_d(\nu_R))} \right)^{4/3}$$

For $\Delta N_\nu < 1$, $\left[\begin{array}{lll} \delta = 0 & : & M_{Z_2} > 1.6\ TeV \\ \delta = 0.002 & : & M_{Z_2} > 2.1\ TeV \end{array} \right.$

For $\Delta N_\nu < 0.3$, $\left[\begin{array}{lll} \delta = 0 & : & M_{Z_2} > 2.8\ TeV \\ \delta = 0.002 & : & Not\ possible \end{array} \right.$

For general θ_{E_6} :

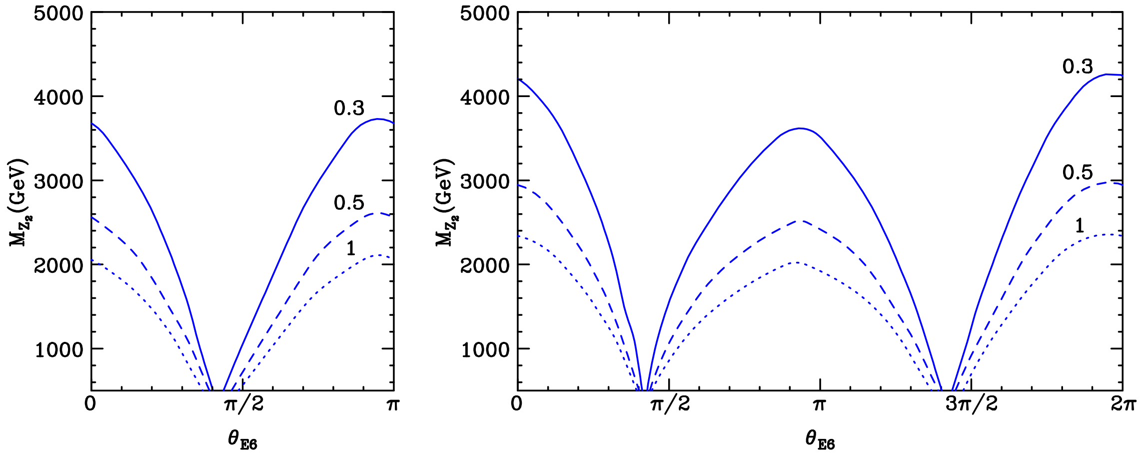
$\delta = 0$ $\qquad$ $\delta = -\frac{g'_Z}{g_Z}\frac{M^2_{Z_1}}{M^2_{Z_2}} \quad \left(\delta = +\frac{g'_Z}{g_Z}\frac{M^2_{Z_1}}{M^2_{Z_2}}\right)$



- For $M_{Z_2} = 0.5$, 1.5, 2.5, 3.5 TeV

- At $\theta_{E_6} = 0.42\pi$ (1.42π), $Q(\nu_R) = 0$ (ν_R not coupled to Z')

$\delta = 0$ $\quad\quad$ $\delta = -\frac{g'_Z}{g_Z}\frac{M^2_{Z_1}}{M^2_{Z_2}} \quad \left(\delta = +\frac{g'_Z}{g_Z}\frac{M^2_{Z_1}}{M^2_{Z_2}}\right)$



M_{Z_2} lower bound for fixed ΔN_ν

- (Except when ν_R does not couple to Z') BBN gives much stronger bound on mass of Z' than any present collider limits.

- The above result is when T_c (quark-hadron transition temperature) is 150MeV.

- For higher T_c, the constraint is even severer. (T_c is between 150 and 400MeV.)

Summary and Conclusion

- We studied, in detail, BBN constraints on Z' properties with a E_6 motivated TeV-scale $U(1)'$ model.

- TeV-scale Z' model suggests ordinary see-saw may be forbidden because of non-zero $U(1)'$ charge for ν_R.
  Our model assumes 3 (almost) massless Dirac ν_R's.

- ν_R interacts super-weakly (due to super-heavy Z') and gives only diluted contribution to energy density.

- ^4He abundace from BBN gives most stringent constraint on Z' mass unless ν_R's are not coupled to Z'.
  (Mostly, $M_{Z'} \gtrsim$ multi-TeV)